Measuring currents in submarine canyons: Technological and scientific progress in the past 30 years

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ABSTRACT

The development and application of acoustic and optical technologies and of accurate positioning systems in the past 30 years have opened new frontiers in the submarine canyon research communities. This paper reviews several key advancements in both technology and science in the field of currents in submarine canyons since the1979 publication of *Currents in Submarine Canyons and Other Sea Valleys by* Francis Shepard and colleagues. Precise placements of high-resolution, high-frequency instruments have not only allowed researchers to collect new data that are essential for advancing and generalizing theories governing the canyon currents, but have also revealed new natural phenomena that challenge the understandings of the theorists and experimenters in their predictions of submarine canyon flow fields. Baroclinic motions at tidal frequencies, found to be intensified both up canyon and toward the canyon floor, dominate the flow field and control the sediment transport processes in submarine canyons. Turbidity currents are found to frequently occur in active submarine canyons such as Monterey Canyon. These turbidity currents have maximum speeds of nearly 200 cm/s, much smaller than the speeds of turbidity currents in geological time, but still very destructive. In addition to traditional Eulerian measurements, Lagrangian flow data are essential in quantifying water and sediment transport in submarine canyons. A concerted experiment with multiple monitoring stations along the canyon axis and on nearby shelves is required to characterize the storm-trigger mechanism for turbidity currents.

1. INTRODUCTION

The publication of the American Association of Petroleum Geologists *Studies in Geology 8: Currents in Submarine Canyons and Other Sea Valleys* (Shepard et al., 1979) marked a significant milestone in submarine canyon research. Although there had been studies on the topics of submarine canyon hydrodynamics and sediment processes in various journals since the 1930s (Shepard et al., 1939; Emory and Hulsemann, 1963; Ryan and Heezen 1965; Inman, 1970; Drake and Gorsline, 1973; Shepard, 1975), this book was the first of its kind to provide description and discussion on the various phenomena discovered in submarine canyons and sea valleys, presenting the most detailed field data collected with state of the art instrumentation deployed at locations in almost all large water bodies (oceans, seas, lakes) on Earth. In the three decades since the Shepard et al. (1979) book, the submarine canyon research community has seen large strides in both science and technology. New instruments with high precision and sampling frequencies that were not imaginable 30 yr ago are being developed and utilized. New discoveries are being made in the field and laboratory and new theories are being formulated based on those discoveries (see review in Allen and Durrieu de Madron, 2009). I do not attempt here to review all aspects of canyon hydrodynamics (e.g., numerical and physical modeling on turbulence mixing or exchanges between canyons and continental shelf and/or slope); instead, I review and summarize several key advances made in the past 30 yr in the research of submarine canyon hydrodynamics that are directly related to sediment transport. Herein I review technological advances including field and laboratory instrumentation as well as data analysis, then review a number of key advances in submarine canyon hydrodynamic processes, and summarize and discuss several future research challenges constructed primarily for submarine canyons in temperate climate, such as the California coast.

2. TECHNOLOGICAL ADVANCES IN CURRENT OBSERVATION IN SUBMARINE CANYONS

2.1. Instrumentation

Instrument development has come a long way in the past 30 yr. The greatest leap in the technology of flow measurements was the transition from mechanical to acoustic current meters. Advances in sensor development and semiconductor engineering drastically improved the precision and accuracy, from centimeter per second to millimeter per second, of current meters, reduced the physical size of the instruments, and increased their data storage capacities. The concurrent reduction of the power draws of sensors and the improved battery technology made long field data collection possible. Coupled with improved mooring designs, it is now quite routine to have continuous year-long observations of flow fields in canyons (Khripounoff et al., 2003; Xu et al., 2004), a big improvement compared to the days- and month-long time series collected 30 yr ago (Shepard et al., 1979). Improvement in material, design, and machining afforded sensors and pressure cases that can now withstand pressure at full ocean depth, and thus currents can now be measured thousands of meters below the sea surface (Khripounoff et al., 2003, 2009; Xu et al., 2002, 2004).

The most significant leap forward in flow measuring technology is probably the development and wide use of acoustic Doppler current profilers (ADCP). Before the ADCP was invented, velocity profiles were measured at only a few locations in the canyon by current

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meters deployed at different depths on a single vertical mooring line (Fig. 1). Limited by resources and complexities in mooring design and deployment, a typical mooring consisted of 3–5 point current meters that spanned a few hundred meters vertically (Ferentinos et al., 1985; Hunkins, 1988; Xu et al., 2002; Palanques et al., 2005). These limited numbers of points were clearly insufficient to fully resolve the current profile. An ADCP, however, can provide current profiles consisting of 20 or more data points within the same vertical span depending on the frequency of the sound source, water depth, mooring configuration, and sampling rate. For example, a low-frequency (75 kHz) ADCP system has a bin size (distance over which data are averaged) of tens of meters, while a high-frequency (1000 kHz) can have a bin size as small as 5 cm. Another advantage of the ADCP is its nonintrusive nature, which allows in situ measurements in highly energetic and hazardous flows such as turbidity currents. Although ADCP started to appear on the mass market in the early 1980s, most of the installations were either downward-looking from ships or upward-looking on bottom platforms deployed on continental shelves, estuaries, and lakes. It was not until early 2000 that ADCPs were mounted on subsurface moorings to measure current profiles in submarine canyons (Xu et al., 2004). ADCPs can also be mounted on a vessel looking downward to collect velocity profiles when the vessel is at anchor at multiple locations (Petruncio et al., 1998; Flexas et al., 2008), or in transit to provide information on the spatial variability of currents (Wang et al., 2008).

ADCPs are also useful in obtaining, at least semiquantitatively, the concentration of suspended particles in the same water column where velocity profiles are measured. There have been numerous attempts (Thorne et al., 1991; Hay and Sheng, 1992; Holdaway et al., 1999; Gartner, 2004) to convert the acoustic backscatter signal to sediment concentration, with limited success. One major difficulty that remains to be overcome is that the grain size distribution in the water column, and particularly in energetic flows like turbidity currents, is still unknown. Without the grain size information, the attenuation of the acoustic backscatter due to the presence of sediment particles cannot be accurately estimated.

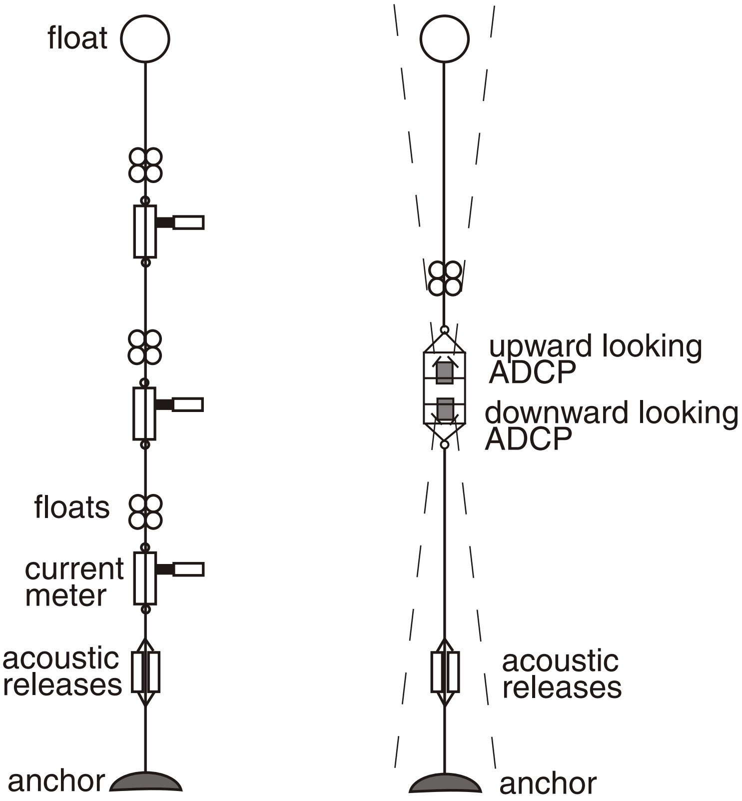

Figure 1. Schematic diagram of typical subsurface moorings used to measure currents in submarine canyons. The mooring on the left is made out of three point current meters that measure time series horizontal (e.g., north and east components) velocities at three elevations. The mooring on the right consists of two acoustic Doppler current profilers (ADCP), one facing upward and the other facing downward. Depending on the frequencies and setup of the ADCPs, they each can typically measure three-dimensional velocities (east, north, and vertical) at 20+ different elevations at vertical intervals ranging from centimeters to tens of meters. Collectively the two ADCPs record the same amount of data equivalent to 40+ point current meters mounted on one mooring.

2.2. Seafloor Mapping

Detailed maps of seafloor bathymetry are very important for correctly and accurately collecting and interpreting current observations in the areas of complex topography such as submarine canyons. Multibeam maps are a vast improvement over the old bathymetric charts, as can be seen by overlaying a shaded relief map of bathymetry based on a multibeam survey on top of an old bathymetric contour of a canyon. Traditionally the majority of flow measurements in submarine canyons are obtained from moorings. In areas where the topography often varies on scales of a few hundred meters, good bathymetry maps are essential to place the moorings at a desired location. In addition, good bathymetry greatly aids the interpretation of observations that may be strongly influenced by the surrounding topography. An accurate bathymetric map and three-dimensional multibeam images along with precise global positioning system (GPS) data and accurate acoustic release mechanisms can enable scientists to deploy the instrumented moorings to the planned locations (Xu et al., 2010; Fig. 2).

The use of remotely operated vehicles (ROVs) and automated underwater vehicles (AUVs) in submarine canyon research greatly improved the accuracy of both seafloor mapping and instrument placement on the seafloor. Guided by a multibeam bathymetry obtained from a surface vessel that has a resolution of meters, an AUV equipped with a specially fitted multibeam system can collect bathymetric data with centimeter-scale resolution (Paull et al., 2010). Such high-resolution topographic maps allow researchers to pinpoint the planned locations for instrument deployment. In addition, the high-resolution images of bed morphology from the multibeam and stratigraphic profiles from a seismic profiling system such as Chirp (compressed high-intensity radar pulse) can aid researchers understanding the flows that generated the topography and stratigraphy. Based on these data, the ROV is capable of installing instruments right on the spot in deep and very complex environments such as the Monterey Submarine Canyon (Paull et al., 2003; 2010).

2.3. Quality and Quantity of Time-Series Data

Armed with improved instruments and advanced mooring technologies, researchers have been able to simultaneously collect detailed current velocity profiles and other oceanographic data in submarine canyons from multiple moorings deployed along and across the canyon, with multiple current meters and other sensors attached to each mooring, and for periods of time as long as 2 yr (Hotchkiss and Wunsch, 1982; Ferentinos et al., 1985; Butman, 1988; Hunkins, 1988; Palanques et al., 2005; Khripounoff et al., 2009; Xu and Noble, 2009). These long time-series data that have sampling rates of a few minutes allow a wide variety of techniques to be used to describe, analyze, and interpret the observations. For example, the spatially and temporally high resolution data matrix of current velocity and temperature and salinity are essential in computing the variations of isotherm displacement as well as density and velocity structures, all of which are key ingredients for characterizing the amplitudes and frequencies of internal (baroclinic) tides (Hotchkiss and Wunsch, 1982; Matsuyama et al., 1993; Petruncio et al., 1998; Rosenfeld et al., 1999; Palanques et al., 2005; Wang et al., 2008). Translation of computer programs into a common, user-friendly computing language such as MATLAB has made the processing and analyzing these data sets much easier (Pawlowicz et al., 2002).

The high-resolution, high-frequency data collections also made the determination of detailed spectral characteristics of the canyon flows possible. Auto spectra and cross-spectra of the velocity and temperature and salinity data define the spatial (both vertically in water column and horizontally along a canyon) variations of the energy of inertial, tidal, and higher-frequency processes (Hotchkiss and Wunsch, 1982; Butman, 1988; Xu and Noble, 2009). Rotary spectra, a close variant of the spectra of vector variables, use the two circular components, the amplitude and phase of both clockwise and counterclockwise motion, to determine the rotary characteristics in flow fields (Emery and Thomson, 2001; Jarosz et al., 2007). An advantage of rotary spectra is that rotary properties like spectral energy and rotary coefficients are invariant under coordinate rotation, hence the steering of currents by canyon topography may be ignored. Since one of the rotary components (clockwise in the Northern

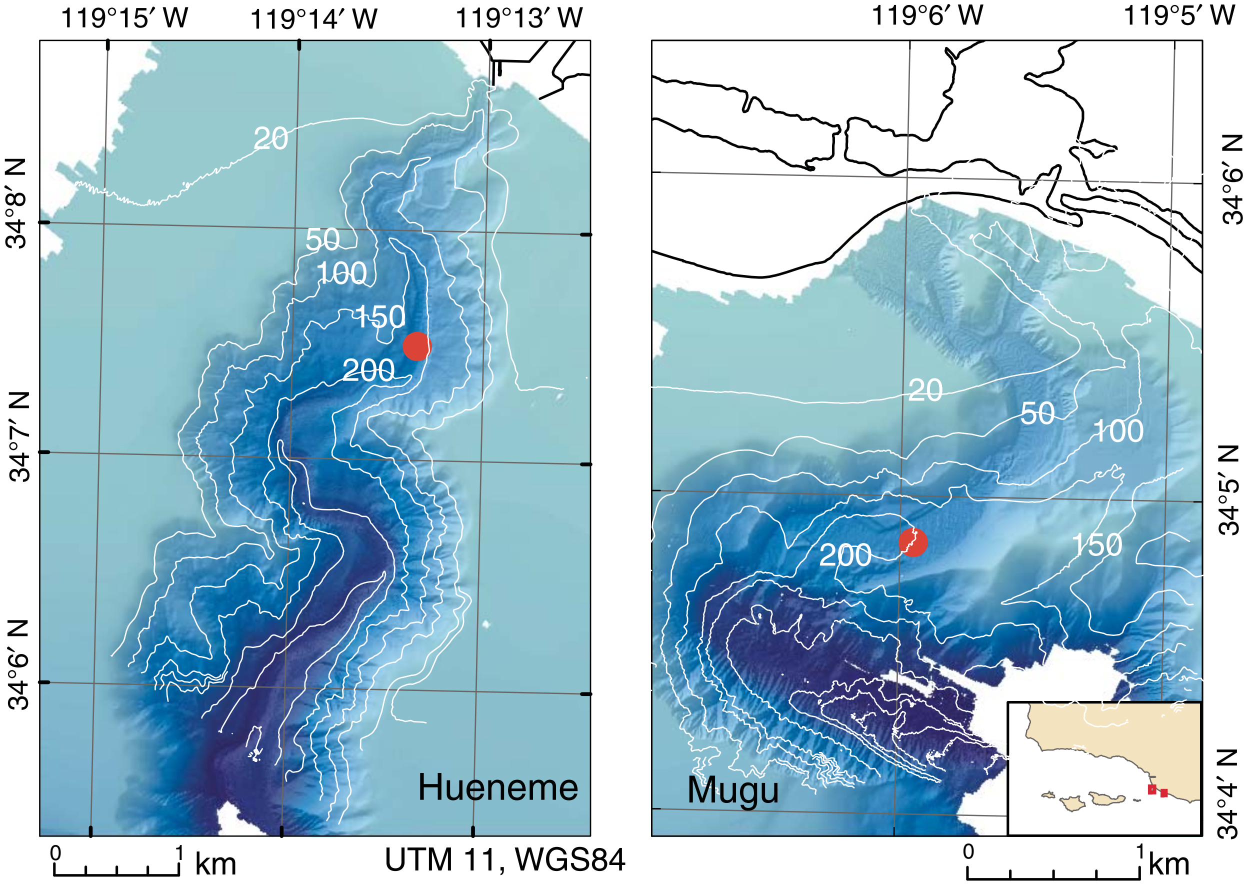

Figure 2. Multibeam bathymetry of Hueneme (left) and Mugu (right) submarine canyons, with mooring locations shown (red dots). In this particular deployment the moorings needed to be in water depth shallower than 200 m, limited by the depth rating of the instruments. The meter-resolution multibeam bathymetry made the following tasks possible: (1) locate a site in the thalweg (axis) of the canyon; (2) ensure the sites to be in a relatively straight section of the canyon to minimize the complexity of the measured current velocities; (3) find the accurate water depth; and (4) safely deploy the moorings. Other instruments such as temperature, salinity, and pressure sensors can also be attached at different heights on the mooring line. UTM—Universal Transverse Mercator.

Hemisphere, counterclockwise in the Southern Hemisphere) very often dominates the velocity field, analysis of only one component is usually sufficient (Emery and Thomson, 2001). Wavelet power spectrum, a sophisticated version of complex demodulation, is particularly useful in determining how spectral energies of different frequencies vary over time (Grinsted et al., 2004; Xu and Noble, 2009).

The ray theory has been successfully utilized in both laboratory and field studies to explain the generation, propagation, and dissipation of internal tidal energy on continental slopes (Cacchione and Wunsch, 1974) and in submarine canyons (Hotchkiss and Wunsch, 1982; Baines, 1983; Gardner, 1989; Lafuente et al., 1999; Palanques et al., 2005). The energy of internal tides (1) propagates upward toward the canyon head; (2) propagates parallel to the canyon bottom; or (3) is reflected back down canyon, depending on whether the ratio of s/α is smaller than, equal to, or greater than unity. Here s is the slope of the canyon floor, and the slope of the rays for internal tides is

$$\alpha^2 = \frac{\omega^2 - f^2}{N^2 - \omega^2}, \qquad (1)$$

where ω is the internal tidal frequency, f is the Coriolis parameter, and N is the Brunt-Vaisala frequency.

3. IMPROVED UNDERSTANDING OF CURRENTS IN SUBMARINE CANYONS

3.1. Current Intensification

After studying hundreds of current records collected in dozens of submarine canyons, Shepard et al. (1979) concluded that dominant current components in submarine canyons have oscillations roughly at the mean tidal frequencies. Field studies and modeling since then more accurately defined and explained the frequency structure and two other key properties specific to currents in submarine canyons: (1) currents are dominated by baroclinic (internal) tides, and (2) currents are intensified both vertically toward the canyon bottom and horizontally toward the canyon head. In Hudson Canyon (North Atlantic), the energy of the internal wave field grew by a factor of five from the mouth of the canyon to a position well inside the canyon (Hotchkiss and Wunsch, 1982). In Baltimore Canyon (North Atlantic) (Hunkins, 1988; Gardner, 1989), tidal currents were observed to intensify toward the canyon floor. Similar bottom intensification was observed in Lydonia (North Atlantic; Noble and Butman, 1989), La Linea (Alboran Sea; Lafuente et al., 1999), Kaoping (offshore Taiwan; Wang et al., 2008), and Monterey Canyons (Petruncio et al., 1998; Kunze et al., 2002; Xu and Noble, 2009). The bottom intensification is clearly displayed in the shape of tidal ellipses of the major constituents. While the ellipses above the canyon rim are nearly circular, they become stronger, with an almost rectilinear flow that is locally aligned parallel to the canyon axis near the canyon floor (Hunkins, 1988; Xu and Noble, 2009). This strong bottom intensification of canyon currents at tidal or higher frequencies seems to occur in both up-canyon and down-canyon currents (Wang et al., 2008).

When internal waves at the canyon mouth propagate toward the canyon head, the power densities of the currents increase in the along-canyon direction for both along- and cross-canyon velocities, although the former is far more energetic than the latter (Hotchkiss and Wunsch, 1982). This was observed in Lydonia Canyon (Butman, 1988), where currents in the inertial, semidiurnal, and higher frequency bands increased toward the canyon head and toward the floor. At places where the slope of the canyon floor is near the critical slope for semidiurnal and inertial frequency (see equation 1), the energy in these two frequencies reached the maximum (Butman, 1988).

Hotchkiss and Wunsch (1982) rearranged equation 1 to the form

$$\omega_c^2 = \frac{N^2\alpha^2 + f^2}{\alpha^2 + 1}, \qquad (2)$$

and demonstrated that V-shaped submarine canyons focus the energy of internal waves that enter the canyon from the offshore boundary toward the canyon head if the internal wave frequencies are greater than a critical value ω_c. For internal waves that enter from above the canyon, the V-shaped canyons focus the internal wave energy toward the canyon floor if the frequencies are less than the critical frequency ω_c that is derived from equation 2, but with α being the slope of the canyon walls (see Fig. 1 in Hotchkiss and Wunsch, 1982). In Xu and Noble (2009, in Monterey Canyon) it was shown that internal waves within the frequency range between 0.06 cph (cycles per hour) and 0.35 cph should focus into the canyon both from above and from the canyon mouth. In other words, semidiurnal internal tides and higher frequencies are focused but lower frequencies are not.

3.2. Turbidity Currents and Other Episodic Strong Flows

Shepard et al. (1979) identified two major flows that control the dynamics of submarine canyons. One is the internal waves and/or tides that are responsible for the current oscillations and the near-bottom and headward intensifications (see Current Intensification discussion); the other is turbidity currents. Turbidity currents are episodic, strong, down-canyon flows of water and suspended sediment that are concentrated in the canyon axis near the bottom. They are the primary mechanism for transporting sediment from the coast, through the canyon, and into the deep basin. Generations of researchers have attempted to measure these currents in situ and document their effects in various environments (Inman et al., 1976; Hay, 1987; Prior et al., 1987; Khripounoff et al., 2003; Paull et al., 2003; Xu et al., 2004). However, because of the episodic and violent nature of turbidity currents, it is not uncommon that instruments deployed to measure these phenomena are destroyed or moved by the down-canyon flow (Inman et al., 1976; Prior et al., 1987; Paull et al., 2003). It is ironic that the velocity, frequency, and displacement caused by turbidity currents can sometimes be determined from the final positions of instruments damaged during deployments (Garfield et al., 1994; Paull et al., 2003; Hsu et al., 2008). In mid- to high-latitude submarine canyons such as those in the Gulf of Lions (Mediterranean), gravity flows due to dense water cascading have been recognized as a major driver to transport water and sediment down canyons (Canals et al., 2006; Palanques et al., 2006; Puig et al., 2008). When this density flow is first formed by sinking cold water on the shelf, it travels slowly downslope at ~30 cm/s, and does not necessarily carry large amount of suspended sediment. As soon as the dense water enters the head of canyons near the shelf break, it accelerates down the steeper slope in the canyon to a speed as high as 80 cm/s (Puig et al., 2008). During this acceleration phase, it is possible for the cascading cold water to entrain enough sediment from the canyon floor to transform into a turbidity current.

Field studies carried out between 1993 and 2007 in Monterey Canyon provide some of the most extensive observations of turbidity currents (Fig. 3). Debris flows and turbidity currents have occurred often in Monterey Canyon in geological time (Normark and Piper, 1991), but only recently were in situ measurements available that enabled researchers to characterize and parameterize the vertical profiles of velocity and sediment concentration in a turbidity current (Xu et al., 2002, 2004; Paull et al., 2003). From 2002 to 2005 there were 12 sediment transport events observed at different water depths in the axis of Monterey Canyon (Barry et al., 2006). Not all these events were necessarily turbidity currents, but the currents in the events were energetic enough to move, knock down, and bury instrument platforms (Paull et al., 2003). Moorings at a particular site can record the passing of a turbidity current, but unless the mooring arrays had short spatial scales the array may not be able to define the extent of that event. Even though existing mooring data are not dense enough for an assessment of the spatial scales of the observed turbidity currents, the depth at which turbidity currents currently occur can be inferred based on movement of moorings, sediment morphology in the canyon axis, or the inferred lack of sediment transport. In the example shown in Figure 3, moorings at site N and other locations further up canyon often recorded passing turbidity currents (Xu et al., 2002, 2004), but these recorded events did not reach W, a site ~50 km further down canyon from site N. In addition, the frequent monitoring of the skeleton of a dead whale found in the axis of Monterey Canyon at 2890 m, ~10 km down flow from site W, showed no evidence of any disturbance from 2001 to 2005, indicating that no turbidity current passed the site (Paull et al., 2006). These measurements and observations suggest that present-day turbidity currents in Monterey Canyon are too small to reach beyond 2500 m water depth. This is in part because the thalweg of Monterey Canyon is substantially wider down canyon of the 2500 m isobath (Fig. 3). A turbidity current from up canyon would probably lose both speed and sediment concentration after entering the much wider channel, and thus dissipates quickly, unless the turbidity current is a large, ignitive, and self-accelerated flow (Parker et al., 1987). Historically turbidity currents were large enough to reach the Monterey fan-valley system in geological time (Normark and Piper, 1991), and created and maintained the existence of Monterey Canyon. Study of sediment cores taken across the channel near the Shepard Meander, ~130 km down flow from site W (Fig. 3), showed that the most recent past occurrence of such large turbidity currents was more than 150 yr ago (Johnson et al., 2005). Note that the impact of the modern-day turbidity currents can go beyond 2500 m water depth. The body of turbid water (the remnant of the already vanished turbidity current) can become an intrusion into water of similar density and continue to flow offshore along this density surface.

The two most important parameters of a turbidity current are velocity and sediment concentration. In situ velocity data are still sparse despite decades of efforts in collecting field data from fjords, lakes, inlets, and submarine canyons (Prior et al., 1987; Lambert and Giovanoli, 1988; Zeng et al., 1991; Khripounoff et al., 2003; Paull et al., 2003; Xu et al., 2004). The maximum velocity of turbidity currents observed from current meters (ADCP or otherwise) ranged from 120 cm/s in Zaire Canyon (West Africa; Khripounoff et al., 2003) to nearly 280 cm/s in Hueneme Canyon (California; Xu et al., 2010). When velocity profiles are available, the bulk parameters such as the thickness

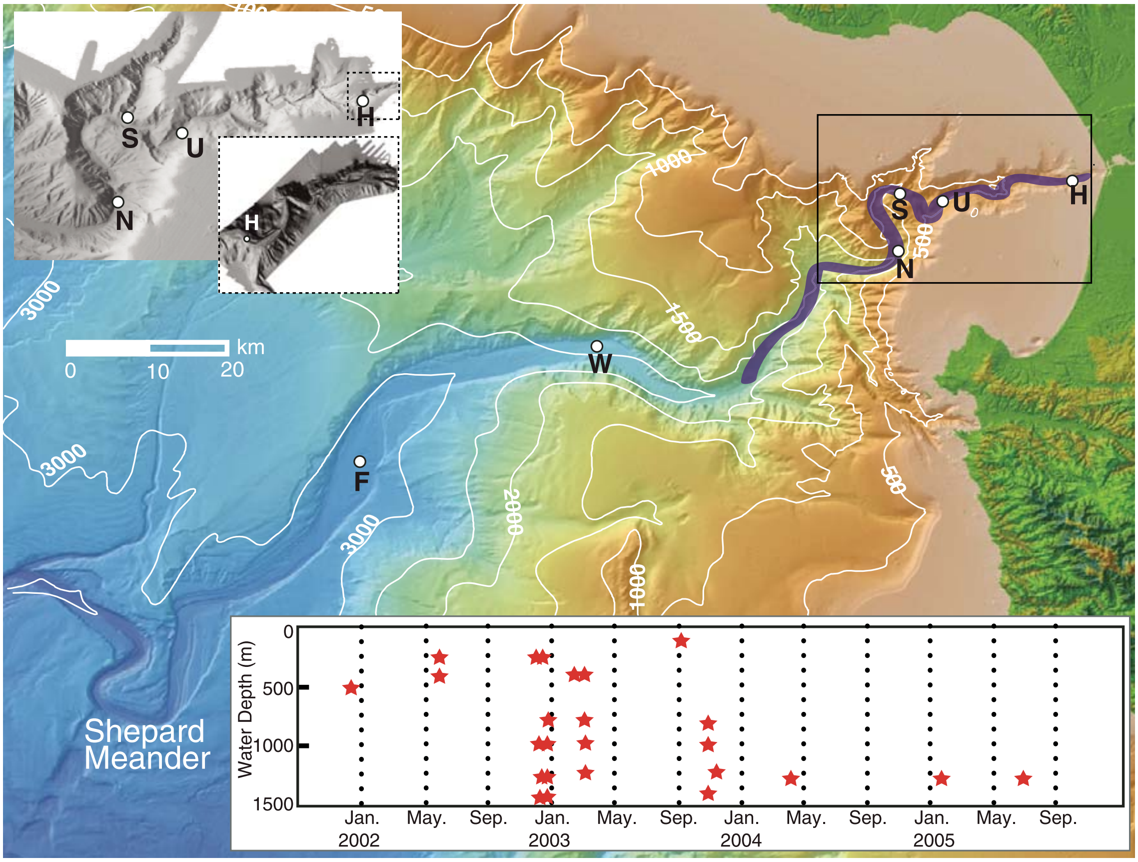

Figure 3. Locations of the U.S. Geological Survey mooring sites overlaid on the shaded relief bathymetry of the Monterey Submarine Canyon. The top left inset shows the close-up of the canyon head. The inset at the bottom right corner shows the timing and location of the observed turbidity current events (from Barry et al., 2006). The thick purple line along the canyon signifies the region where present-day turbidity currents often occur. The last major turbidity current that passed the Shepard Meander was 150 yr ago (Johnson et al., 2005). The water depths of the mooring sites are: F—3223; W—2837; N—1445; S—1020; U—820; H—255 m.

and depth-averaged velocity of a turbidity current can be calculated. For example, ADCP data from Monterey, Hueneme, and Mugu Canyons in California showed that the present-day, small-scale turbidity currents were 50–200 cm/s in depth-averaged velocity and 15–50 m in thickness (Xu, 2010).

The sediment concentration within a turbidity current is even more difficult to measure directly because of the current's destructive nature. To my knowledge, a transmissometer time series obtained from Monterey Canyon (Fig. 4) is the only in situ measurement from within a field turbidity current. The sensor was located 10 m above the canyon floor on mooring N deployed at 1445 m water depth (Fig. 3; Xu et al., 2004); therefore, its data represented the concentration in the center of the 50-m-thick turbidity current. Assuming that the suspended sediments inside the turbidity current were composed of 50% sands and 50% silts, and applying the composite calibration relation from Xu et al. (2002), the highest concentration during the peak of the current reached up to 2.1 g/L. For comparisons, this concentration would be 4.1 g/L if the suspended sediments were all sands. Note that for a few hours during each of the two events the transmissometer was blacked out (zero transmission), suggesting that the highest concentration could have been much greater.

For most of the turbidity current data, where direct measurements of sediment concentrations are unavailable, the acoustic backscatter signal from ADCPs can be used for estimating sediment concentration after the acoustic signals are corrected for two-way transmission loss due to attenuation and scattering (Holdaway et al., 1999; Gartner, 2004). Comparable results were obtained from applying this method to the turbidity current events in Monterey Canyon (Rosenberger et al., 2006). Another empirical method to assess the bulk sediment concentration in the body of a turbidity current, whose bulk speed is known, is to apply the Chezy-type equation (e.g., Bowen et al.,1984) backward (Xu et al., 2010). The validity of these two methods relies heavily on the accuracy of estimating the grain size value within the turbidity currents.

The existing data are not sufficient to allow the researchers to determine exactly how the turbidity currents originated (Xu et al., 2004). A total of 18 months of ADCP measurements in Monterey Canyon at site H in 255 m water depth near the head of Monterey Canyon (Fig. 3) from the 2005 and 2007 experiments showed no sign of events resembling the turbidity currents observed in previous deployments. This suggests that a subannual frequency of turbidity current occurrence (Barry et al., 2006) is not a robust assumption for the entire Monterey Canyon. A possible explanation for the scarcity of turbidity currents at site H is that some, or most, of the events observed in previous experiments originated in places deeper than 255 m (the water depth of site H). This would suggest that submarine landslides, including the breaching processes of Mastbergen and van den Berg (2003), are a major cause of the observed turbidity currents in Monterey Canyon. If so, it would further suggest that submarine landslides might occur more often than previously thought (see discussions in Ferentinos et al., 1985). However, the mooring deployment at site H was not concurrent with the deployment at sites N, S, and U. Thus, the lack of events at site H in 2005 and 2007 does not exclude that turbidity currents observed at sites U, S, and N during 2002–2003 originated at the canyon head, caused by, for example, storm wave set up (Inman et al., 1976).

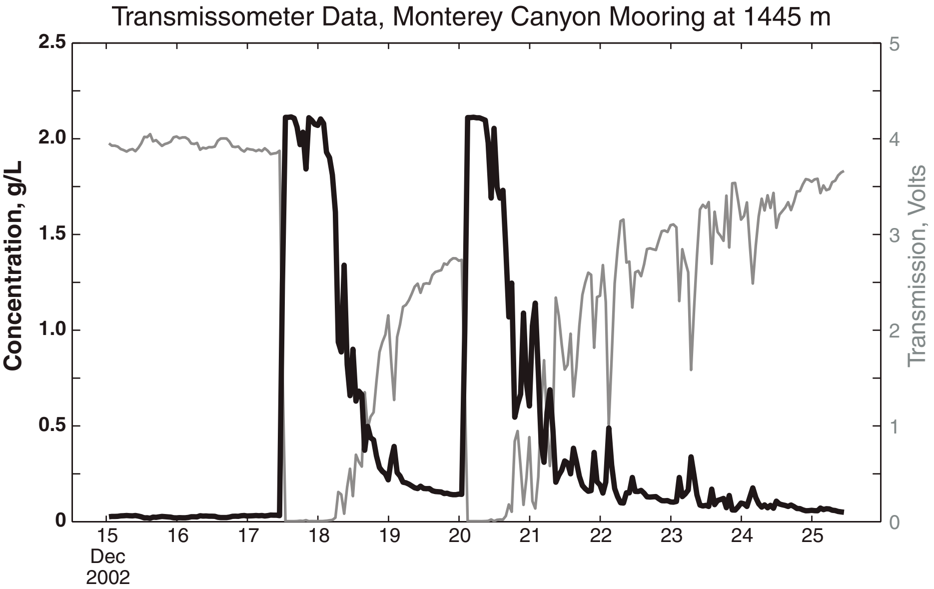

Figure 4. Time series of measured light transmission (gray line) and converted sediment concentration (dark line) during two turbidity current events. The data were measured 10 m above canyon floor from a mooring deployed at 1445 m (site N; see Fig. 3) in Monterey Canyon. Note that during the peak of each turbidity current, the transmissometer was blacked out (zero transmission) for several hours.

4. FUTURE CHALLENGES

In the past 30 years, researchers have made significant strides in documenting and understanding the processes that occur in submarine canyon. In particular, some of the progress discussed here and other knowledge gained from numerical modeling studies (Baines, 1983; She and Klinck, 2000; Allen and Durrieu de Madron, 2009) have advanced our understanding of hydrodynamics and sediment transport in submarine canyons. Despite these advances some key questions related to water and sediment flows in submarine canyons remain partially or completely unanswered. Three of these questions are discussed in the following.

4.1. Lagrangian Measurements

Nearly all flow measurements in submarine canyons are made with moorings at fixed locations; therefore, only Eulerian current patterns are obtained from the time-series data. In studies where mooring stations are far apart, these Eulerian flows, and in particular the mean flows, may suggest significant convergences or divergences in the transport of water and sediments (Hunkins, 1988; Xu and Noble, 2009) that are not corroborated by physical evidence, such as erosion and/or deposition patterns or local bathymetrical changes. This is because Eulerian means are fundamentally different from Lagrangian means, which are a truer representation of water particle motion. Eulerian means can arise from differential vertical mixing in the bottom boundary layer during up-canyon or down-canyon flow, from an asymmetry in the up-canyon and down-canyon fluctuation caused by the geometry of the canyon, or from a net flow that balances a Reynolds flux caused by the internal wave fields (Butman, 1988). This residual Eulerian current may not indicate a net Lagrangian transport of water or sediment. Thus direct measurements of the Lagrangian flow are needed in order to correctly estimate the water and sediment transport through submarine canyons.

It is still logistically difficult to measure Lagrangian currents in the field. The work strategy presented in Figure 5 is still just a concept. In a section of a submarine canyon that is relatively simple in bathymetry and curvature, and also longer than the tidal excursion of the dominant frequency (e.g., M2), a series of acoustic transducers are deployed at predetermined locations on both sidewalls of the canyon. These transducers are used to track and determine the position of a neutrally buoyant float later released to the middle of the canyon to mimic the water particle motion at a certain depth. The transducers are deployed in such a way that at all times at least three transducers communicate with the acoustic float so an accurate position of the float can be triangulated. In theory, multiple floats of distinct frequencies and different buoyancies may be used simultaneously to represent the Lagrangian motion of different depths (or isopycnal layers). Because of the high possibility that the float package will get caught by canyon walls while moving along the canyon, it is prudent to have a mechanism to periodically release a new float package for needed redundancy.

4.2. Cause of Turbidity Currents

Piper and Normark (2009) summarized the initiation processes for turbidity currents into three categories: sediment failure due to earthquake and other submarine landslide processes, direct flow of freshwater sediment-laden flows (hyperpycnal flows), and storms and other oceanographic processes. The most spectacular and well-known modern-day turbidity current is probably the event associated with the 1929 Grand Banks earthquake that cut submarine cables on the slope (Heezen and Ewing, 1952). For the limited number of earthquake-generated turbidity currents in the past century, all data related to the speed or structure of the turbidity currents were circumstantial or inferred from events such as the destruction of communication cables (Hsu et al., 2008). The physical structures in turbidity currents could not be observed directly because earthquakes are not predictable. Flow-measuring instruments in the path of such large-scale turbidity current are almost certain to be destroyed. The inability to directly observe turbidity currents generated by earthquakes will continue for the foreseeable future unless forecasting earthquakes becomes attainable and field instruments are drastically improved.

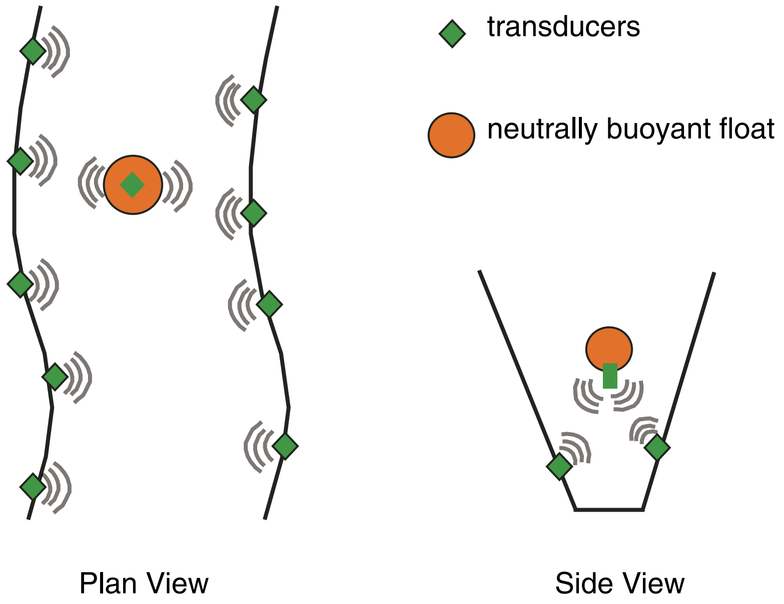

Figure 5. Idealized sketch of how Lagrangian current is measured in a submarine canyon. The positions of the transducers (green diamonds) deployed on the sidewalls are known. Each transducer communicates to the transmitter inside the neutrally buoyant float and records the travel time between them. After recovery of the transducers, instantaneous positions of the float can be estimated by triangulating the distances between the float and three or more transducers at any moment. Lagrangian velocities can then be calculated from the instantaneous positions.

In the meantime, research efforts can be focused on determining the sources of smaller scale, less destructive turbidity currents found mostly in submarine canyons. Known triggering mechanisms include high river discharge (Mulder and Syvitski, 1995; Khripounoff et al., 2009), submarine landslides (Mastbergen and van den Berg, 2003; Johnson et al., 2005), storm waves (Inman et al., 1976; Xu et al., 2002, 2004, 2010), and cascading of dense shelf water (Canals et al., 2006). Most of these studies are correlative in that they suggest, but do not prove, the sources and mechanisms. What remains to be determined is the probability of, and mechanisms involved in, the generation of a turbidity current either in parallel or in a sequential chain reaction. In the case of Monterey Canyon and other similar canyons on the U.S. west coast, the temperate climate and lack of larger rivers directly connecting the canyons likely rule out dense water cascading and high river discharge as causes of turbidity currents in these canyons. Sedimentation induced by convergence of storm waves at the canyon head and possible subsequent collapse of the rapidly deposited sediment pile (or submarine landslide) are more likely the trigger of the observed turbidity currents. Inman et al. (1976) recognized that surface waves set up a higher water level over the shelf than over the canyon head. This setup differential generates a local circulation that moves water from the shelf toward the canyon head. This effect is especially strong during storms, when higher wind and/or wave setup on both sides of the canyon generate longshore currents that converge on the canyon head. The majority of turbidity currents observed in Monterey Canyon were in fact correlated with local storm waves (Xu et al., 2004; Barry et al., 2006). A well-designed field program, in which shelf and/or surf-zone processes and canyon currents are measured simultaneously, assisted by numerical modeling, should be able to shed light on how increased wave heights and water-level setup near the canyon head initiate turbidity currents in submarine canyons. Such field measurements would include (1) wave sensors from offshore, to the shelf, and to within the surf zone so the directional wave propagation could be characterized; (2) along-shore measurements of wave and water-level properties on both sides of the canyon for estimating wave-inducing setup as well as the littoral sediment transport; (3) along-canyon moorings that monitor the occurrences and measure the parameters of turbidity currents; (4) pre-event and post-event high-resolution mapping of the canyon head to detect the location and size of the collapse(s); and (5) measurements of geotechnical properties (e.g., pore pressure) of the rapidly accumulated sediment deposit at the canyon head to help estimate the probability of failure or liquefaction due to cyclic loading, such as seismic shaking or oscillatory surface waves (Ishihara and Yamazaki, 1984).

4.3. Synthesizing the Currents in Submarine Canyons

Hotchkiss and Wunsch (1982, p. 416) attempted to generalize the dynamics of major canyon processes with the hypothesis that "there ought to be some simple, physical principles governing the intensity of water movement in canyons, so that global catalogue of measurements in the different regions of every canyon need not be required to describe the interaction of water and topography." Like many analytical and numerical models built on idealized assumptions, the generalization tends to break down when applied to a situation with, for example, more complex bathymetry or density stratification structure. However, this weakness does not undermine the usefulness of the generalization. A simple but well-constructed and physically sound model is deemed helpful in designing the location and placement of field instruments for measuring current circulation pattern around and within submarine canyons (Klinck, 1996; Hickey, 1997; Boyer et al., 2000; Waterhouse et al., 2009).

Traditionally, the physical modeling approaches (e.g., Garcia, 1994; Sequeiros et al., 2010) are to use parameterization to generalize a physical process, such as the flow field in submarine canyons, when the amount of data from field and/or laboratory measurements reaches a critical mass. One successful attempt used the large amount of good-quality field data collected in submarine canyons to generalize both the field and laboratory data together, such as the normalized velocity profile of turbidity currents (Xu, 2010). However, the difficulties of synthesizing these diverse data sets are tremendous when these generalization approaches are applied to more complex dynamic processes. Canyon measurements from many parts of the world in the past 30 yr reveal qualitatively that internal tides in canyons are: (1) dominated by semidiurnal internal tide; (2) most energetic near the canyon head; and (3) anisotropic, i.e., greater kinetic energy is found along the canyon rather than across the canyon. The community is still uncertain on how to quantify and parameterize these generalized canyon properties. Further progress will require concerted field campaigns, such as the well-conducted North Atlantic Slope and Canyon Study (Butman, 1988) and similar studies in Baltimore Canyon (Hunkins, 1988) and Monterey Canyon. Clearly, advanced instrumentation and numerical and physical modeling skills are to play key roles in such endeavors.

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